Ten years of modeling the Deepwater Horizon oil spill

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ABSTRACT
Since the 2010 Deepwater Horizon (DWH) oil spill, the Gulf of Mexico Research Initiative (GOMRI) has studied the oil spill from the perspectives of ocean environment, ecosystems, socioeconomics and human health. As GOMRI sunsets in its tenth year after the DWH oil spill, synthesis efforts recently took place to assess the accomplishments of the program. In this paper, we report on DWH modeling as part of GOMRI's Synthesis and Legacy effort. We compile a list of 330 published applications by GOMRI, the Natural Resource Damage Assessment (NRDA), and others studying the DWH oil spill and look at a wide range of subjects, tools, achievements, and integration with field research. We offer highlights and synthesis based on discussions and public webinars held in 2019 and 2020. We synthesize the significant achievements and advancements that have been made in integrating the various disciplines and domains from a modeling perspective. There was a large diversity of tools used, including at least 74 unique modeling systems. Most studies employed circulation models. These hydrodynamic models were often coupled to wave, river, and atmosphere models, as well as representations of high pressure physics and oil chemistry. Several research groups used Lagrangian transport models and statistical inference to track subsurface oil. Some coupled biophysical models were also employed to study oil fate and weathering, larval transport, biological effects, and population dynamics. In a few cases, such bio-physical models were linked to marine populations and to humans through socioeconomics effects and ecosystem services. We consider models made for response planning and remediation, damage assessment, and restoration planning. There are relatively few socioeconomic or human health models, although those few examples make good use of biophysical modeling products. Our conclusions offer some insights on how the development of new tools has better prepared us for studying environmental management challenges in the Gulf of Mexico.

1. INTRODUCTION

1.1. GOMRI legacy

It is the end of a ten-year research program studying the Deepwater Horizon (DWH) oil spill. The independent Gulf of Mexico Research Initiative (GOMRI) was funded by a U.S. $500 million commitment from BP. GOMRI's goal was to "improve society's ability to understand, respond to and mitigate the impacts of petroleum pollution and related stressors of the marine and coastal ecosystems, with an emphasis on conditions found in the Gulf of Mexico" (from the GOMRI Mission Statement). GOMRI solicited proposals for fast-response studies in 2010 and issued six more requests for proposals from 2011 to 2018. These were directed at research consortia (consisting of four or more institutes), smaller groups, and individual researchers. Altogether, 394 research groups, 17 consortia, and at least 2849 researchers from around the world contributed over the past 10 years (GRIIDC 2020). More than 1260 peer-reviewed publications have been produced and more than 3154 data sets have been archived on the Gulf of Mexico Research Initiative Information and Data Cooperative (GRIIDC) data repository, comprising at least 83 TB of data (GRIIDC 2020).

As GOMRI ended in 2020, synthesis and legacy has become a focus. A Synthesis and Legacy Committee was established in 2019 to oversee eight areas.

- Core Area 1: plume and circulation observations and modeling.
- Core Area 2: fate of oil and weathering.
- Core Area 3: ecological/ecosystem impacts.
- Core Area 4: human health and socioeconomic impacts.
- Core Area 5: ecosystem services.
- Core Area 6: microbiology, metagenomics and bioinformatics.
- Core Area 7: integrated/linked modeling systems.
- Core Area 8: knowledge exchange with user communities.

This paper reviews the integrated and linked modeling systems in Core Area 7. These bring together theory and tools developed in areas 1 through 6 into a common predictive framework. Core Area 7 is further divided into Areas 7 A and 7B. These areas distinguish operational modeling from synthesis modeling, although they may be better viewed as including 'tactical' versus 'strategic' modeling tools. We include both types in this review because there is a high degree of overlap in concept, tools, data, and expertise.

Herman Stachowiak's "General theory of models" (1973) reminds us that a model is only a limited reproduction and reduction of the real world. Models only include things assumed to be important by the creators and are designed with a user in mind and specific questions in mind. Operational and synthesis models are designed for a certain purpose, and for a certain time. Therefore, a model should be understood by answering four questions. A model of what? For whom? For what purpose? For what time period? The distinction between tactical and strategic models is most relevant in terms of the motivation and perspective of the user. Tactical models operate over a short time horizon, hours or days. This minimizes assumptions and makes them agile tools for response planners. Strategic models are more inclusive and heuristic in nature because they offer a framework on which to reconcile many different types of information, often cross-disciplinary. They simulate over weeks, years, or decades and may be employed for damage assessment and recovery planning. They are directed towards managers, stakeholders and academics.

There are many examples in GOMRI of cross-disciplinary integrated modeling systems. Systems may be loosely connected by data flow from one model to another, or more tightly federated to permit feedback among domains. Examples include: use of velocity fields from hydrodynamic models in Lagrangian ocean models, use of oil constituent distribution from ocean models to evaluate exposures and effects for ecosystem models, and further chaining of ocean and ecosystem processes to derive inputs for human health and socioeconomic models. The preponderance of ocean/ecosystem models discussed below is consistent with the comparatively recent emergence and integration of socioeconomic and health models. Many unexploited opportunities exist for connecting physical and ecosystem variables to socioeconomic and health models. This might entail one-way causal connections to enhance the measurement of impacts, or full feedback to assess how perceptions of spills condition responses.

In this paper, we attempt to synthesize the advancements that have been made in integrating the various disciplines and domains from a modeling perspective. We compile a list of published applications by GOMRI researchers, the Natural Resource Damage Assessment (NRDA), and others studying the Deepwater Horizon Oil Spill between 2010 and 2020. We looked at the range of subjects studied, tools used, use of model coupling, and integration with field research. This allows us to offer some synthesis, based on discussions and public webinars in 2019 and 2020 arranged as part of a Core 7B review. Synthesized here are the significant areas of achievement and advancements. Our conclusions offer some insights on how the development of new tools has better prepared us for studying environmental management challenges in the Gulf of Mexico.

2. METHODS

2.1. Data collection

We reviewed modeling applications since 2010 focused on studying the DWH oil spill. The literature search was based on project websites, citations, an informal Core 7B knowledge survey, and discussions with modelers, leads, and the GOMRI Research Board. We documented peer-reviewed articles, technical reports, book chapters, and conference proceedings. In a few cases, we cite GRIIDC datasets if no other published methodological or application papers from a particular model or research group could be located. In addition to the literature search, we highlight discussions from the Core 7B synthesis effort. These included a meeting of GOMRI modelers at the Gulf of Mexico Oil Spill and Ecosystem Science Conference in Tampa in 2019, a series of webinars and virtual workshops in the spring of 2019, and a series of virtual workshops in May 2020. The goal was to recognize the full range of work done by GOMRI and the impact that GOMRI has had on the state of integrated modeling. Besides this article, there are two other manuscripts resulting from the GOMRI Core 7B synthesis webinars and meetings. Solo-Gabriele et al. (2021) uses causal loop diagrams to visualize connectivity of human and natural systems. Mauritzen et al. (unpublished manuscript) uses system dynamic modeling to illustrate ecosystem connections made in integrated modeling.

We concentrated on numerical modeling. We have not documented any applications of empirical models, though many numerical models incorporate statistical methods in parameterization, simulation, and validation. There were many empirical models developed as part of GOMRI (Masi et al., 2014; McDonald et al., 2017) but these deserve their own review. Ordination, analytical models (Chiri et al., 2019; Chan et al., 2015; Kuehl 2014), and conceptual models (Zeinstra-Helfrich et al. 2015, 2016) were also not considered despite being active areas of study.

2.2. Classification of models

As we are interested in integrative modeling, we emphasize model coupling, especially across disciplines. Some models are better referred to as modeling systems as they integrate modular components. All subcomponents will be identified here. We include models that provide boundary conditions and common packages used for data assimilation (e.g. NCODA: Navy Coupled Data Assimilation system; Cummings 2005; Cummings et al., 2013). All published algorithms for model forcing, parameterization, and boundary conditions are included here as well (COARE 3.0, Fairall et al., 2003; K-Profile Parameterization KPP, Large et al., 1994; OTIS, Egbert et al., 1994).

For the purposes of categorizing the cross-disciplinary nature of DWH modeling, we considered whether applications addressed the following four scientific domains: 1) the ocean physical and chemical environment, 2) the biological system, 3) socioeconomics and 4) human health. These categories are consistent with other Core 7B Synthesis and Legacy products (https://gulfseagrant.org/oilspilloutreach). We further divided the applications into 11 categories related to the subject of the study. These categories refer to the interests of the applications and do not necessarily reflect the capabilities or most common uses of the models involved. Models may be used across many categories. The categories are: 1) circulation/mixing,

2) abiotic transport (far field), 3) oil fate, 4) biotic transport, 5) biological impacts, 6) other plume dynamics, 7) turbulence/local mixing, 8) water chemistry, 9) atmosphere, 10) oil spill response support, and 11) other. Circulation/mixing represent a wide range of hydrodynamic studies that do not include explicit particle tracking. Abiotic transport refers to the large body of work tracking reference particles. Models in this category treat particles as passive and chemically/biologically inert, but some use a multi-fraction droplet size distribution (DSD) model to affect processes such as buoyancy, deposition rate and oil fate. Oil fate models may add chemical or biological breakdown or dispersion submodels. Biotic transport of larvae or eggs implies coupling to biological models where particles can interact with other biological components (Paris et al., 2013; Bracco et al., 2019). We made particular note of models that crossed two or more scientific domains. Finally, we noted the degree to which models use field data to guide the modeling effort.

3. RESULTS

3.1. Overview of DWH modeling work

Supplemental Table S1 shows 330 numerical modeling applications for the DWH oil spill by GOMRI, NRDA and other authors. All these applications were published between 2010 and 2020. Table S2 shows original references for each numerical modeling system employed. We will hereafter refer to the items in Table S1 as applications, and items in Table S2 as models (even though Table S2 includes a few packages for boundary conditions, parameterization, and data assimilation). Table 1 arranges the applications by subject of study.

3.2. 65%: Physical models

A majority 65% of the studies (214/330) used physical modeling, sometimes including chemistry (Fig. 1). At least 11 consortia, 6 individual investigator/research grants (from GOMRI RFPs II, V and VI), and NRDA efforts contributed these types of products. Topics included circulation, turbulence/mixing, plume dynamics, particle transport/ deposition and physical chemistry. Circulation models resolved mixing dynamics based on the contributions of coupled atmosphere, ocean, and wave (Xue et al., 2015; Huang et al., 2013; Curcic et al., 2016; Sorourian et al., 2020) and/or by taking surface oil feedback to ocean, atmosphere and wave into account (Zheng et al., 2013), or by including detailed river plume dynamics and their effects on hydrocarbon transport (Schiller and Kourafalou 2010; Kourafalou and Androulidakis 2013; Androulidakis and Kourafalou 2013; Greer et al., 2018; Hole et al., 2019). Particle transport studies used Lagrangian models with passive reference particles either integrated into the circulation model directly (ROMS: Shchepetkin and McWilliams 2005; FVCOM: Zheng and Weisberg, 2012) or as a stand-alone tool (CMS: Paris et al., 2012, 2013; TRACMASS: Do¨o¨s et al., 2013). These systems used innovative model coupling of wave models and river effects (Huang et al., 2013) and surface oil's effects on the atmosphere-ocean-waves coupling (Bourassa et al., 1999; Le Henaff et al., 2012), incorporated dispersant effects on oil transport (Reed et al., 1995, French-McCay et al., 2005, Paris et al., 2012, French-McCay et al., 2015a, 2018a,b,c,d), and potentially in-situ skimming and burning (Lehr et al., 2002, Buchholz et al., 2016, French-McCay et al., 2018c,d). Some far-field modeling studies have used measured currents, as well as data produced by circulation models (e.g., French-McCay et al., 2021).

3.3. 22%: Physical-biological coupled models

Another 22% of studies (80/330) coupled physical models with biological models (Fig. 1). The most common uses included Lagrangian particle tracking of eggs and larvae (by GISR, DEEP-C, CIMAGE and RFP V:Shay) (see research.gulfresearchinitiative.org for a complete list of GOMRI consortia and individual researcher awards). For example, the Coupled Ocean Atmosphere Wave Sediment Transport model (COAWST: Warner et al., 2010; Zambon and Warner 2014) employed by the GISR and CIMAGE consortia couple physical processes (hydrodynamic, atmospheric, wave/turbulence from ROMS, HYCOM, WRF, and SWAN) with larval transport models, such as LTRANS (North et al., 2008 and Connectivity Modeling System (CMS, Paris et al., 2013).

Physical and chemical processes come together in oil fate models such as oil-CMS, SIMAP and OSCAR (French-McCay 2003, 2004, Paris et al., 2012, Lindo-Atichati 2016, French-McCay et al., 2018a,b,c,d; Reed et al., 1995, Perlin et al., 2020, Vaz et al., 2021). TAMOC is a nearfield plume model with chemistry Gros et al., 2017, 2020). Within GOMRI, the CIMAGE, DROPPS and GISR consortia engaged in this work. Socolofsky et al. (2015) reviewed near- and far-field modeling with OSCAR (with Plume-3D), oil-CMS, OILMAP/OILMAPDeep, as well as particle tracking (LTRANS, CMS), and droplet formation models (VDROP-J). Physical-biological model coupling also helped to address research questions concerning water quality/hypoxia, nutrient cycling and red tides, and fisheries impacts (e.g, Weisberg et al., 2016a; Lenes et al., 2013; Justic and Wang, 2014). NRDA faced a similar task of modeling oil transport, fate and effects using the spill impact model application package (SIMAP, French-McCay et al., 2015a,b,c, 2018a) to evaluate the impacts of the DWH, further developing modeling methods used by French-McCay (2003, 2004). French-McCay et al. (2018a,c) (BOEM/NRDA) utilized ROMS, HYCOM, NGOM, NCOM and atmospheric models NARR, NOGAPS and CSFR along with SIMAP to evaluate oil transport and fate sensitivity to circulation.

3.4. 5%: Biological models

Less than 5% of modeling studies (15/330) used only biological modeling (Fig. 1). These included population dynamics, niche/habitat suitability models, matrix population models, and individual based models (by CARMMHA, ECOGIG, DEEP-C, LADC-GEMM, RFP V: Saul). Studies by the CARMMHA Consortium developed age- and cohort-based population matrix models for bottlenose dolphins and fish species (Schwacke et al., 2017). These were notable for integrating expert opinion. Powers and Saul (2018) used agent based modeling to assess fish movements.

3.5. 5%: Physical-biological-social coupling

Full integration across physics, biochemistry and socioeconomic domains was achieved by 5% of studies (17/330). These studies coupled an oil fate model with an ecosystem model to incorporate dispersal, burial, evaporation, biodegradation, and uptake-depuration dynamics. The model coupling therefore accounted for exposure and toxicity in 4D and was used to determine both lethal and sublethal impacts (Ainsworth et al., 2018; Dornberger et al., 2016; Berenshtein et al., 2020). Modeling these processes was supported by targeted laboratory experiments (e.g., Mitchelmore et al., 2020). Table S1 shows applications using AMSEAS, FVCOM, HYCOM, oil-CMS, or SIMAP for circulation/oil fate data, while applying the ecosystem models HABSIM, Ecopath with Ecosim (EWE), or Atlantis. From these, metrics can be computed to measure impacts on human beings: fisheries value (Ainsworth et al., 2018; Berenshtein et al., 2019), food security (Suprenand et al., 2019), toxin exposure (Walsh et al., 2016; Lenes et al., 2013), environmental services (Rohal et al., 2020), impacts on shore based industries (Court et al., 2019). In this last example, Court and colleagues went an extra step, using an input-output model, IMPLAN, to interpret catch predictions from Atlantis in terms of impacts on tourism and hospitality. This example therefore represents the longest chain of quantitative reasoning in DWH modeling products, linking ocean physics, biology, and socioeconomics.

3.6. Modeling products by consortia

Fig. 2 shows modeling products by consortium. Numerical modeling was utilized most by the CIMAGE, CARTHE, DEEP-C and GISR Consortia, with DROPPS, ECOGIG and various small research groups also making contributions. Circulation modeling was a major area of study across consortia, small research groups, NRDA. CARTHE, DEEP-C, and GISR applied these circulation models to abiotic transport questions. These studies used simulated drifters to answer near- and far-field transport questions. In addition, CARTHE, DEEP-C, DROPPS, GISR, and small research groups applied this work in the areas of plume dynamics, local mixing, and biotic particle transport. CIMAGE had the most publications relating to the study of biological impacts, but ECO-GIG, LADC-GEMM, and small research groups contributed. Implications of oil spill response were mainly supported by the oil spill risk and response planning community outside of GOMRI (e.g, Buchholz et al., 2016; Crowley et al., 2018; French-McCay et al., 2018d; 2019; Bock et al., 2018). However, much GOMRI science was ancillary to this topic. GOMRI was responsible for improvements in understanding and model formulations for oil transport and fate. Fig. 3 shows the number of models coupled per publication. Fifty-eight percent of studies (192/330) used a single model. The rest coupled two or more models together.

3.7. Advances in ocean physics and chemistry

3.7.1. Near-field modeling

Near-field modeling represents the movement of oil near the well-head. Socolofsky et al. (2015) identified the following areas of active study in DWH near-field modeling: bubble and droplet generation, plume modeling, intrusion formation, coupling to circulation models, particle tracking, and bubble and droplet fate modeling. Achievements in near field modeling of the DWH oil spill include an accurate representation of dissolved gas and dissolution of the liquid fraction (Gros et al. 2017, 2020). This controls how gas bubbles affect turbulent mixing and entrainment processes (Fabregat et al., 2017). This incorporates the influence of oil chemistry on plume characteristics. Plume modeling in GOMRI has benefited from laboratory work in high pressure environments and better model formulations for hydrate formation and dissolution (Gros et al. 2017, 2020).

3.7.2. Far field modeling

Major circulation models employed in DWH modeling include hydrostatic primitive equations models (HYCOM, ROMS, FVCOM, NCOM, etc.) or non-hydrostatic Large Eddy Simulations (LES) (Fig. 4). Oil-CMS, SIMAP, GNOME and OSCAR may be better called oil fate models as they utilize circulation model results to integrate particle movement (e.g. oil rising velocity interacting with ocean temperature and salinity, Paris et al., 2012), and model oil breakdown (e.g., dissolution and photooxidation, Vaz et al., 2021) and dispersal processes (see below). There are many more circulation models that are used for DWH modeling. Models of smaller spatial domains, utilizing models such as FVCOM, SUNTANS, or ROMS, may be nested inside the GOM or global-scale circulation models (most often HYCOM and ROMS) to provide boundary conditions. Circulation models ranged in scale from individual estuaries to sub-mesoscale and basin scale spatial domains (Aizinger et al., 2013; Cambazoglu et al., 2017; Cui et al., 2018; Taylor 2018). We believe a major advancement in far field modeling following the DWH oil spill is the development of a system of multiple-scale numerical models that span the river-wetland-estuary-shelf-open ocean continuum and covers physics, geomorphology, biogeochemistry, water quality, and coastal food webs in the Gulf of Mexico. When dealing with large spills, floating oil can substantially modify wind and ocean waves, which in turn modifies the movement of the spill. The importance of surface fronts was also identified, relating them to freshwater outflows, explaining the dynamics using submesoscale physics, and characterizing dispersive and anti-dispersive properties. Oil can become thicker when impinging on a front, so fronts are important areas for responders to note. Far field modeling in GOMRI has benefited from laboratory work in high pressure environments (Malone et al., 2018; Pesch et al., 2018) and better model formulations for emulsification, hydrate formation, dissolution, and sedimentation (Nguyen et al., 2018; Lindo-Atichati et al., 2016; Perlin et al., 2020; Vaz et al., 2021).

3.7.3. Particle tracking and oil fate

Progress was made in modeling oil dispersion using Lagrangian particle tracking. Liu et al. (2011a) collected a series of early modeling efforts associated with the DWH oil spill, including the rapid response operational models combining satellite imagery inferred oil locations and aerosol formation with trajectory models (Liu et al., 2011c; Mac-Fadyen et al., 2011; DeGouw et al., 2011). Spaulding (2017) provides a recent review of far-field oil transport and fate modeling. In common to these efforts, the movement of oil is resolved in three dimensions and fate processes are represented such as dispersion, spreading, evaporation, entrainment, emulsification, dissolution, biodegradation, photo-oxidation and sedimentation. Examples of these methods for modeling the DWH oil spill includes work done for NRDA and BOEM (French-McCay et al., 2015a; 2018a; b, 2021), CARTHE (UWIN-CM/LASER: Chen and Curcic 2018; Huntley et al., 2011), CIMAGE (oil-CMS: Paris et al., 2012; Perlin et al., 2020), GISR (LTRANS: Chapman et al., 2014) and DEEP-C (Liu et al., 2011b, 2014; Weisberg et al., 2011, 2016b, 2017). Some of the studies employ published tracer advection algorithms such as MPDATA (Smolarkiewicz 1984).

Modeling microbial degradation of oil lags behind modeling efforts in oil transport, dispersion and oil chemistry. Socolofsky et al. (2019) presents a review of simple, first-order degradation models. GOMRI-funded researchers have documented microbial degradation rates and microbial community succession patterns during oil degradation (Kostka et al., 2011; Rodriguez et al., 2015; Huettel et al., 2018). Time series linking in situ petroleum hydrocarbon degradation to microbial community activities allowed predicting a 30-year period for the decomposition of sediment-oil-agglomerates buried in Gulf of Mexico sandy beaches (Bociu et al., 2019; Shin et al., 2019). A searchable genome database cataloguing diversity and global distribution of crude oil-associated microbes was established that provides molecular identification tools and spatial distribution data for models integrating microbial community responses (Karthikeyan et al., 2020). The CSOMIO model (Dukhovskoy et al., 2021) combined simulations of oil with microbial degradation and sedimentation using different computational schemes (COAWST, GENOME, and CSTMS) using a two-way Lagrangian-Eulerian mapping technique also used in Perlin et al. (2020). This enables interaction between all of the modeling components for tracking of hydrocarbons from a source blowout to deposition in sediment, microbial degradation, and evaporation while being transported through the ocean.

Photooxidation of surface DWH oil led to the formation of persistent photooxidized compounds found a decade later. Studies demonstrated that photooxidation modified both biodegradation rates of the surface oil and the effectiveness of aerial dispersant applications. The first step before modeling biodegradation of oil in shoreline sediments, is to model the photooxidative changes and track the transport of persistent photooxidized compounds. Vaz et al. (2021) estimated and tracked the likelihood of photooxidation of Lagrangian oil droplets by coupling the net shortwave radiation from NOGAPS to the oil-CMS. The dose of solar radiation upon a droplet is computed with the intensity of the incoming irradiance at the ocean's surface, the light attenuation coefficient, and the depth of the oil droplets. This new dynamic coupling provides a powerful tool to test oil weathering hypotheses, refine the oil budget during the DWH, and ultimately inform rapid response in future oil spills.

3.7.4. Subsurface oil tracking

Before the DWH, there was no oil spill model that dynamically computed live-oil (gas-saturated) concentrations of oil droplets in the deep sea, though models did take other thermodynamic processes pertaining to high-pressure environments into account (e.g., Johansen 2003; Yapa et al., 2001; 2010; Zheng and Yapa 2002). In DWH modeling, circulation models were effectively combined with 3D Lagrangian particle models (e.g., Weisberg et al., 2011), turbulence, waves, river, atmosphere models, and even biodegradation and oil chemistry to form coupled model systems (Paris et al., 2012). Combined near-/far-field models like OSCAR, SIMAP with OILMAP-DEEP (used for the NRDA, Spaulding et al., 2015, 2017b; French-McCay et al., 2015a; 2018a) and oil-CMS offer important complements to NOAA's work with more tactical response planning models like GNOME. These models consider oil transported at the subsurface and at the surface, coupling near-field and far-field models (Vaz et al., 2019). An important conclusion of these models for DWH is that bubble and droplet rise velocity should be accurately predicted accounting for in situ conditions (Zheng and Yapa 2000) and evolving particle sizes due to various fate processes (Gros et al., 2017; Pesch et al., 2020).

The subsurface oil simulator (SOSim) model (Echavarria-Gregory and Englehardt 2015; Jacketti et al. 2020, 2021; Ji et al. 2020, 2021) offers an alternative Bayesian modeling method for tracking subsurface oil, including the only model written specifically for sunken (bottom) oil, as well as a module specifically for submerged (water column) oil. Starting with the general solution of the advection-dispersion equation, the model accepts 4-D field concentration data collected in initial sampling campaigns as input, to infer the values of model parameters. SOSim further accepts bathymetric data as Bayesian prior information indicating Coriolis forcing and settling of sunken oil. It also inputs alternative fate/transport model output as prior information reflecting hydrodynamic data conditions that influence the movement of sub-merged oil. The approach complements and potentially improves on Lagrangian particle tracking alone by rigorously integrating field data with prior information to provide a ground-truthed forecast representing the relative probability of finding oil in time and space.

3.7.5. Atmosphere/weather forcing

There has been a realization in DWH studies that atmospheric forcing options in models cannot be treated as arbitrary. A large number of circulation studies included atmospheric forcing using models like WRF, COAMPS, and COAWST. Representation of the air-sea interface (atmospheric and oceanic boundary-layer parameterizations) and the selection of the coupling method (inclusion of ocean currents, sea surface temperature, waves, and oil slicks) have a substantial impact on forecasts (Le Henaff et al., 2012; Soloviev et al., 2014; Geng et al., 2016). A novelty for the fate of surface oil is the capability to model dynamically photo-oxidation of oil based on solar irradiance (Vaz et al., 2021). A new solar irradiance module of oil-CMS is coupled with NAVGEM (NAVy Global Environmental Model).

3.7.6. Droplet size distribution (DSD)

Near field modeling of the DWH brought about development of droplet size distribution (DSD) models that can account for the decrease of mean droplet sizes due to dispersant use in subsea dispersant injection (SSDI) (Johansen et al., 2013; Zeinstra-Helfrich et al., 2015; Spaulding et al. 2015, 2017; Zhao et al. 2016, 2017; Li et al., 2017; Gros et al., 2017), therefore affecting transport and degradation of oil (Paris et al., 2012, French-McCay et al., 2018a,b,c,d, 2019). An important advancement is the coding of Lagrangian reference particles as oil droplet entities, with attributes of density and size (Paris et al., 2012; Lindo-Atichati et al., 2016; Spaulding, 2017; Perlin et al., 2020). These can interact with the ocean model temperature and salinity variables to affect rise velocity, terminal velocity and plume characteristics (Paris et al., 2012). Droplet size and rise velocity are two of the most important variables to model the far field oil trajectory and dispersal (Paris et al., 2012; Zhao et al., 2017; Gros et al., 2017; Pesch et al., 2018). Quantification of both biodegradation and dissolution generates a change in the DSD through time (Lindo-Atichati et al., 2016). Oil spill models in the 1980s and 1990s often did not address the DSD for oil blowouts (Nissanka and Yapa 2018). However, numerous experimental and modeling efforts in GOMRI were directed at resolving oil rise and entrainment dynamics in buoyant plume models (Socolofsky et al., 2015; Zhao et al., 2017; Gros et al., 2017; Aiyer et al., 2019; Bracco et al., 2020). Models applied a fundamental log-normal or Rosin-Ramler DSD distribution law (Johansen et al., 2013; Gros et al., 2017; Li et al., 2017; Perlin et al., 2020) or non-fundamental distribution function (VDROP-J) in deep-sea oil spill models. Faillettaz et al. (2021) demonstrated that the choice of probability distribution function of the DSD for far-field modeling is, regardless of the mean droplet size (d50), consequential for oil spill response.

3.7.7. Multiphase droplets

A breakthrough for deep sea blowout modeling is the capability to model multiphase oil droplets. These have a gas and a liquid phase to model the internal degassing process that has been revealed in laboratory experiments (Malone et al., 2018; Pesch et al. 2018, 2019). The gas-saturated oil is subjected to a pressure drop similar to the one observed at the oil platform during the DWH blowout. The oil-CMS has a new degassing module that allows both expansion of gas nucleated within the droplet and dissolution of gas (Pesch et al. In Review). TAMOC also models multiphase droplets, showing that gas dissolution of free gas was rapid out of the liquid droplets while at depth such that oil droplet rise may have little influence from degassing (Gros et al., 2020). However, there has not yet been validation of the percentage of free versus nucleated gas within the liquid oil phase using field data from DWH.

3.8. Advances in biological modeling

GOMRI has advanced the representation of oil spills on both low- and high-trophic level communities. Coupling oil fate and circulation models to ecosystem models has allowed a highly resolved representation of population-level effects in space and time. This is a necessary feature in estimating impacts on exploited species, which are often mobile and spatially partitioned by life stage. This allows us to represent different exposure risks in different types of habitat. These methodologies can be readily extended to other geospatial pulse disturbance problems like toxic algae blooms and hypoxia. Ecosystem models have benefited from the 4D representation of oil concentrations at the short spatial and temporal scales native to circulation models (e.g., SIMAP-Ecospace: Suprenand et al., 2019, French-McCay et al., 2015b,c, 2018a,c,d, CMS-Atlantis: Ainsworth et al., 2018). Uptake-depuration dynamics and dose-response relationships can quantify the effects of oil (French-Mcay 2002, 2003, 2004). The mode of oil uptake by organisms can be represented in biological models to represent transdermal absorption or ingestion (Ainsworth et al., 2018; Dornberger et al., 2016). Methods developed to study DWH were subsequently applied to hypothetical oil spills (Berenshtein et al., 2019; Paris et al., 2020; Suprenand et al., 2019), the IXTOC oil spill (), the Exxon Valdez oil spill (T. Okey, Pers. Comm.), and oil pollution in the Niger Delta (Ndimele, E. Pers. Comm.).

A lot of the discoveries in GOMRI centered around developing a better understanding of physical and biological community connectivity. Many sampling, laboratory, and modeling efforts were devoted to it. Investigating pelagic diet linkages especially has become relevant to recent observations about population connectivity (Paris et al., 2020; Milligan et al., 2018). Coupled HYCOM-CoSiNE modeling allowed deRada (2019) to explore vertical connectivity of pelagic habitat within the planktonic microbial community. Coles et al. (2017) similarly represented microbial communities implicitly using coupled circulation and genomics models (GENOME: Coles et al., 2017). Woodstock et al. (2020) coupled a biochemical model ROMS-NPZD to OSMOSE, an individual-based ecosystem model of the upper food web. FVCOM-HABSIM uses an integrated biological model within a circulation model (Weisberg et al., 2016a; Zheng and Weisberg 2012; Lenes et al., 2013). Walsh et al. (2016) again stimulated trophic connectivity in pelagic food webs to demonstrate that fisheries and oil spills can have cumulative effects. This has direct consequences for human health (Weisberg et al., 2016a).

The theme of connectivity in pelagic food webs was also applied to the study of higher trophic levels. Ainsworth et al. (2018) showed how food web impacts near the wellhead were translated to distant areas through impacts on mobile forage fish populations. Ongoing efforts will determine whether linkages between epi- and mesopelagic communities influence vulnerability to subsurface plumes. Ruzicka et al. (unpublished manuscript) have collaborated with the DEEPEND consortium to develop a set of oceanic food web models (GoMex-ECOTRAN) aimed at quantifying trophic connectivity between epi-, meso-, and bathypelagic depth zones via particle sinking and diel vertical migration behavior. Ongoing simulations with GoMex-ECOTRAN aim to estimate how perturbations to vertical exchange processes and changes to food web structure within each depth zone propagate throughout the entire water column. Woodstock et al. (2021) confirmed that large pelagic fish were highly dependent on mesopelagic forage and therefore potentially vulnerable to deep sea pollution.

A consistent problem with upper food web simulation studies is that fully probabilistic simulations are difficult due to run time limitations in highly resolved spatial food web models (e.g., Suprenand et al., 2019; Ainsworth et al., 2018). Morzaria-Luna et al. (2018) made a major advance in the state of the art by using cloud computing and a statistical emulator to predict Atlantis' responses. Other studies appealed to semi-quantitative expert opinion-based approaches to narrow the parameter space (Suprenand et al., 2019; Schwacke et al., 2017). Other biological models, like the matrix models of Ackleh et al. (2019) can be evaluated using a formal sensitivity analysis.

3.9. Advances in socioeconomics modeling

Few quantitative models of the socioeconomics of oil spills are available. One early attempt was made outside of GOMRI to assess potential fishery damages through a simple value chain model (Sumaila et al., 2012). Court et al. (2017) utilized the travel cost method and input-output analysis model using to evaluate the economic impacts of cancelled recreational trips to Northwest Florida after the DWH spill. An input-output (I/O) model was provided outputs from the Atlantis ecosystem model, with oil-CMS inputs, to evaluate shifts in commercial and recreational fishing activities due to fishery closures resulting from the DWH spill (Court et al., 2019). This included projections for non-consumptive industries like tourism and hospitality. Another example used oil-CMS to simulate fisheries and socio-economic impacts arising from fishery closures (Berenshtein et al. 2019, 2020). In a similar fashion SIMAP integrates the ocean environment and ecosystem domains and provides estimates of ecosystem valuation by providing input to another model, the Offshore Environmental Cost Model (OECM) (BOEM 2016). Finally, one of the GoMRI RFP V projects developed a bioeconomic spatially explicit agent-based model of fisher decision making, behavior, and demersal fish population dynamics (Saul et al., 2020). The model is being used to understand how coupled fisher-fish behaviors interact with hypotheses about oil related toxicological fish mortality, and the spatial fishing closures used to protect seafood safety. The model represents the important institutional components of the system such as the individual fishing quota system, as well as state conditions such as fish and fuel prices, weather conditions, and others.

Part of the difficulty in the integration of socioeconomic models with models within the ecosystem domain is due to the differences in measures and scales. For example, the valuation of fisheries is dependent upon the fish species. Among fish species there is a valuation for commercial versus recreational fishing. Therefore, the ecosystem information requires considerable disaggregation to get at measures that would be useful for socioeconomic models. Socio-economic models are also dependent upon decision-making relevant scales (Yoskowitz et al., 2017). Cash et al. (2006) detail these scales to include jurisdictional, institutional, management, networks and knowledge at the regional to local levels, all of which would influence the linkages needed to ocean environment and ecosystem models. The requirement for time-stepping is also difficult for socio-economic models as they typically rely on fixed price relationships which are only appropriate for static modeling (Court et al., 2019).

3.10. Advances in human health modeling

Human health during environmental disasters is impacted by physical exposures to contaminants and to the emotional stress which has significant impacts on mental health. Mental health may also impact physical health, but these connections, although recognized, have not yet been quantified. Modeling of physical health can be facilitated through risk assessment approaches (NRC 2009; EPA, 2010), which is a process used to estimate the probability of harm. Model setup begins by identifying the hazard (i.e., chemical concentration at point of human exposure) followed by computing exposure through multiple routes (dermal, ingestion, inhalation), and ultimately computing the probability distribution of health risk (Ott et al., 2007). Impacts to physical health are highly dependent upon the specific chemicals in oil. Thus coupling ocean environment models to estimate physical human health impacts requires disaggregating the oil into individual chemical compounds. Crowley et al. (2018) provide an example determining air exposure risks for individual volatile organic compounds). One approach has been developed through BEACHES (Beach Exposure and Child Health Study) for estimating physical health impacts to children who play at oil impacted beaches (Ferguson et al., 2020; Montas et al., 2020). Integration of the BEACHES risk assessment approach would require disaggregation of oil into constituent chemical species to represent oil interactions in water, air and sediments in beach environments. In the context of mental health, conceptual and semi-quantitative models have been established to evaluate cause (disaster direct and secondary effects) and effect (resilience and recovery within a community as measured by economic stability, housing stability, physical well-being, mental well-being, and social role adaptation) (Abramson et al. 2010, 2015).

New models of human systems are needed to represent some processes thought to be important. For example, economic models typically omit a number of social or human capital dimensions with important implications for the long-term evolution of communities, including concepts like resilience that are of clear interest to Gulf stakeholders. In an economic input-output framework such as IMPLAN (2020), education and health care activities do not explicitly produce health, happiness or productivity as outputs. Therefore, a complementary model of off-market phenomena in coastal communities would be a desirable reusable component for future integration of spill impacts on human systems.

Sandifer et al. (2017) describe a conceptual framework for a Disaster Pressure State Ecosystem Service Response Health (DPSERH) model. The framework emphasizes the importance of capturing broad feedbacks for valuing oil spill impacts and guiding response efforts. Since the model is conceptual, it is underspecified relative to a simulatable implementation of the same scope. However, it is a useful road map for integration that highlights multiple features that are missing from the current model portfolio. Subsets of the concept may perhaps be implemented via federation of existing model components. By constructing the model de novo, one would have the advantage of choosing a practical level of detail for each concept. A complementary top-down modeling approach that explores physical-biological-social feedbacks in an aggregate, strategic way, is explored in the accompanying 7B synthesis products by the authors.

3.11. Marriage of experiment and modeling

GOMRI can point to many successful examples of where experiment and observations supported modeling. Physical simulation models benefited from drifter experiments in the 2012 Grand LAgrangian Deployment (GLAD) and the 2016 Lagrangian Submesocale Experiment (LASER) projects. These were organized by the CARTHE Consortium (Poje et al., 2014) with the purpose of investigating particle dispersion and submesoscale features. GLAD released drifters near the DWH site and Louisiana coast. LASER took place in the De Soto Canyon region. LASER deployed even more tracers than the previous GLAD and used ship-based and aerial observations. To accompany LASER, which focused primarily on offshore processes, the Submesoscale Processes and Lagrangian Analysis on the Shelf (SPLASH) took place in 2017, focusing on nearshore submesoscale dynamics (http://carthe.org/).

Another drifter experiment, the Gulf Integrated Spill Response (GISR) tracer experiment was conducted in 2012by the GISR Consortium (Ledwell et al., 2016). Drifters and a chemical tracer were released in the northern GOM. Subsequent cruises monitored the dispersal of the tracer. These programs aim to understand the role of large ocean flows in dispersing oil and resolve problems that some transport models have in representing small-scale convergence zones (Haza et al., 2018). Tracer data were compared with hydrodynamic outputs using SABGOM (He 2016) and ROMS/HYCOM (Bracco et al., 2018; Khade et al., 2017). Drifters were similarly used to validate hydrodynamic models (Beron-Vera and LaCasce 2016). GOMRI-supported hydrodynamic models benefiting from these field observations greatly improved current predictions used for DWH oil transport and fate modeling (North et al., 2015; French-McCay et al., 2018a,c, 2021). There are also experimental data to support near field modeling. For example, Wang et al. (2016) took advantage of a field program to characterize turbulent diffusivity in the northern GOM. This helps control mixing of oil/gas pollutants in plume modeling. Droplet size distribution experiments also informed plume modeling (Johansen et al., 2013; Li et al., 2017). Experimental and field data evaluated by Ward et al. (2018a,b) combined with DWH oil fate modeling demonstrated the importance of photo-oxidation as a fate pathway, previously underestimated.

In a similar way, biological modeling was supported by field and laboratory research. Field studies were designed concurrently with modeling efforts and with attention to addressing knowledge gaps in modeling. Physiological experiments in CIMAGE determined the rate of clearance of PAHs in fishes (Snyder et al., 2015) and this was used in the calculation of lethal and sub-lethal effects in fish populations (Dornberger et al., 2016). High pressure experiments helped set biodegradation rates for oil fate simulations and pressure-induced degassing using oil-CMS (Lindo-Atichati et al., 2016, Pesch et al. in review). ROV observations of reef fish communities helped calibrate toxicological impacts in ecosystem simulations (Ainsworth et al., 2018). Plankton and fish sampling, including that supported by NRDA and GOMRI, informed vertical and horizontal biological distribution models used for NRDA injury modeling (French-McCay et al., 2015b,c) and connectivity modeling for benthic species (Paris et al., 2020). Sediment chemistry measurements (Montagna et al., 2013; Valentine et al., 2014; Stout and German 2018; Passow and Stout 2020) helped modelers better understand and model impacts on the demersal food web due to marine oil snow sedimentation and flocculent accumulation (MOSSFA) (Quigg et al., 2016; Burd et al., 2020). That collaborative effort helped show the mechanism of MOSSFA enrichment of the detritus-based food web.

4. DISCUSSION

4.1. GOMRI modeling legacy

The volume and quality of modeling work in GOMRI belies the substantial technical and logistical challenges in achieving model integration across disciplines and systems. GOMRI provided a consistent focus on a large but well-defined research problem that held an urgent connection to human health and well-being. In that context, the remarkable pace and innovation is easy to understand, and also the value of synthesis modeling. The notable achievements in synthesis modeling rested on close collaborations between data providers and modelers, and between scientists in different disciplines. An estimated 1260 total publications resulted from GOMRI (GRIIDC 2020). The list of 330 modeling applications identified here represents a sizable part of the total scholarly output.

DWH modeling may have benefited from an economy of scale as researchers shared many common resources. By 2021, GOMRI modeling rests on a mature collection of data, well-established protocols for data archiving and exchange from GRIIDC, and a still expanding library of methods and applications in the public domain. The well-attended annual GOMOSES Conference offered reliable opportunities for synergies within and outside of GOMRI. Other shared resources were managed by GOMRI administration. These included assistance in publication, education and outreach, networking, and coordination. The GOMRI Research Board provided oversight and coordination, responding to new discoveries for example by establishing the Marine Oil Snow Sedimentation and Flocculent Accumulation (MOSSFA) working group. That cross-consortia group coordinated research efforts associated with oiled marine snow. The MOSSFA working group influenced modeling and led to discoveries about benthic food webs (Dornberger 2018).

For modeling, long time series are important and the continuity of research funding that GOMRI offered over the last 10 years supported that need. The consistency was more valuable since the pre-spill reference data were so insufficient (Joye 2015). Seven consortia were funded by two or more sequential awards (DROPPS, CWC, CIMAGE, CARTHE, ECOGIG, RECOVER, ADDOMEx). The long-term interests of GOMRI offered a rare chance for iterative observations, where modeling helped to direct field observations (Weisberg et al., 2015).

Cooperation outside of GOMRI was strengthened with the conclusion of the lengthy injury assessment and NRDA claim settlement (DWH Trustees 2016). At that time, all NRDA data and assessment information became publicly available. Resolution of the damage assessment phase also enabled increased cooperation between NRDA and non-NRDA researchers. Many researchers, supported by GOMRI as well as the oil spill response community, utilized these vast data sets made publicly available by the NRDA, as well as data collected under GOMRI funding. The publications of GOMRI-sponsored research and improved hydrodynamic modeling developed under GOMRI funding greatly improved the accuracy of oil transport and fate modeling by academia over those performed for the NRDA by oil consultants (French-McCay et al., 2018a; c, 2021). This and other research will continue to make use of the valuable data sets collected from the Gulf of Mexico and coastal areas.

4.2. A foundation in ocean physics

There were a variety of hydrodynamic and particle tracking systems, each offering individual strengths by which we could examine the oil spill from different perspectives. The high inshore resolution of FVCOM (up to 150 m in estuaries and inlets) was suitable to model local factors associated with algal bloom dynamics (Weisberg et al., 2016a), which is an important link to human health implications due to the potential for aerosolization of toxins. Zhong and Bracco (2013) showed the value of having different spatiotemporal resolutions available for understanding Loop Current dynamics. Chapman et al. (2014) similarly demonstrated the value of having a range of resolutions available. They nested a Gulf-scale model (ROMS-SABCOM) with a shelf model (ROMS) and a bay model (SUNTANS) to represent seamless movement of oil into estuaries.

Significant developments in far-field circulation modeling owe partly to development in both near-field plume and turbulence modeling. Outputs from nearfield models are important to far field models, such as buoyant plume trapping and intrusion dynamics, particle slip velocity, hydrocarbon pseudo-components, and droplet size distributions. Thus, the physics of oil dispersal and oil fate required close coupling between near-field plume dynamics and circulation models, with wave, river, and atmospheric models contributing. There were many such examples of modeling coupling and even hybrid approaches which modeled near- and far-field dynamics in an integrated system (e.g., Chen et al., 2018; Paris et al., 2012; Vaz et al., 2019).

Lagrangian particle tracking was used with both near- and far-field models and reference particles represented the transport of the bulk oil and its concentration. Oil fate models were further linked to biodegradation, photooxidation, and biological dispersal routines. New laboratory experiments in high pressure physics, oil chemistry, and biology supported this effort. Emulsification, hydrate formation, dissolution, sedimentation, and biodegradation were examined. Lagrangian tracking partitioned the oil into different chemical species based on a particle size distribution model where each particle size can have unique physical and chemical properties. Multi-fraction particle models allowed modeling dissolution (Lindo-Atichati et al., 2016; Perlin et al., 2020). This allowed better study of subsurface dispersant injection as we could contrast the behaviour of oil with and without the presence of dispersants (Berenshtein et al., 2019; French-McCay et al., 2017; 2018d; Paris et al., 2012). This was a prescient matter for the DWH response as both surface and subsea dispersant injection were used. Data assimilation tools including NCODA and SODA were used often. Going forward, heuristic Lagrangian models such as SOSim and oil-CMS may become important tools for locating and forecasting the position of oil based on real-time data, for emergency response decisions, damage assessment, and study. Thus, we had a well-articulated 4D picture of oil transport and fate. This provided a strong foundation on which to build biological/community and socioeconomic modeling.

4.3. Biological connections

As many as eight consortia and four individual awards contributed to biological modeling. One popular area of study involved the use of biotic transport models to study the movement of larvae, zooplankton, bacteria, and ichthyoplankton. Many of the low trophic level and plankton models used Lagrangian methods, but there were also examples of plankton community interaction models (Desai et al., 2019; Lenes et al., 2013). There were many more examples of community models operating at high trophic levels using Atlantis, Ecopath with Ecosim, ECOTRAN, matrix models, or other approaches.

Population connectivity was a common theme in biological studies (Paris et al., 2020). Food web connectivity was examined by several authors using food web models. The connection between epi- and mesopelagic food webs is likely to remain a long-term research interest in the GOM. The large biomass and energy demands that the vertically migrating mesopelagic community places on epipelagic production suggests that events impacting either the epipelagic or the deep-pelagic communities can propagate widely throughout the entire water column. There was a strong case made through the combined observations of DEEPEND and CIMAGE that deep water oil spills like DWH pose a threat to mesopelagic communities. That threat is potentially affected by the use of dispersants, which has implications for food web dynamics (Morzaria-Luna et al., in review).

Connections between demersal and pelagic food webs remains an important open question, which was considered by GOMRI in detail. These connections were assessed using far-field modeling (Johnston and Bernard 2017), genetic approaches (Bracco et al., 2019), field observations (Murawski et al., 2018), and modeling (Dornberger et al., 2016). GOMRI-sponsored models that explicitly include diel vertical movement processes and trophic connectivity between the epipelagic and deep pelagic, such as Atlantis and GoMex-ECOTRAN, are being applied to simulate how pulse disturbances (i.e., modeled by mortality, recruitment, or growth forcing functions) at different depth zones propagate throughout the water column and ecosystem. Horizontal connectivity through food web effects and animal movement were demonstrated to be important factors in damage assessment in both the DWH and IXTOC oil spills (Ainsworth et al., 2018).

4.4. Human systems

Efforts to understand socioeconomic impacts stand out as the most integrative projects in GOMRI and DWH studies, potentially spanning physical, natural, and human systems. Socioeconomic impacts were often based on fisheries impacts, but also considered were shore based industries, recreation, and ecosystem services. There were not many researchers working on these problems compared with other physical, chemical and biological modeling interests. Human health and socio-economics modeling (other than fisheries impacts) consisted of less quantitative modeling methods, with a few exceptions. Walsh et al. (2016) used lower trophic level community modeling to estimate impacts of fishing and oil spills on asthma triggers and red tides (Walsh et al., 2016). Other authors calculated impacts on ecosystem services, including carbon sequestration and food security (Rohal et al., 2020; Suprenand et al., 2019).

Due to the paucity of models in the human health and socioeconomic domains, there appear to be many opportunities for connecting ocean-ecosystem models to enhanced human system models. At least two approaches may be fruitful. 1) Coupling existing ocean-ecosystem models to existing economic models. This would likely resemble extensions of the existing 5% of models that already integrate physical, biological and socioeconomic knowledge domains (Table S1, col F.). These models may allow valuation of ecosystem components and respond to bottom-up environmental drivers. 2) Creation of new health and socioeconomic models that address important feedbacks, particularly between mental and physical health and socioeconomic activity, and between perceptions of risk and welfare that shape behavior and disaster response. Results from coupled oil spill models that integrate socioeconomics and human health could be used to assess potential risks and societal level impacts of decisions made during and after clean-up efforts. Model-based assessments could provide additional critical information to decision makers about the long-term impacts of their decisions.

4.5. New modeling tools

In Stachowiak's General Theory of Models, the motivation of the modeler or client influences model design as much as any other factor. When we consider the diversity of stakeholders and the diversity of economic, social, and cultural interests affected by the oil spill, a wide range of modeling capabilities indeed must be needed to capture all the processes of interest. GOMRI modeling has greatly expanded our state of knowledge and put much more of the ecosystem under experimental control. This is reflected in the diverse list of applications. Stakeholder interests are interconnected and synthesis modeling can show us where interests align and where trade-offs between competing interests exist. These tradeoffs are inevitably connected with oil response decisions. For example, the use of dispersants influences the relative exposure of surface, inshore, deepwater/pelagic, and benthic habitats. The use of dispersants therefore affects which resources and stakeholders are likely to be impacted most by the oil (Paris et al., 2012; 2018; French-McCay et al., 2018d; Bock et al., 2018). There is also a trade-off in the dispersal of the oil that can be examined with oil fate and effects models, with possible links through natural and human systems. The applications identified here address needs of emergency personnel, managers, scientists, and many other stakeholders. Thus, GOMRI's mandate to improve society's ability to respond to oil pollution was well-supported by modeling.

The model applications explore impacts on different systems and at different temporal and spatial scales. Short- and medium-term modeling studies focused on plume dynamics, fate of oil, and aftermath for coastal industries and seafood safety, while long-term modeling focused on ecosystem state changes and recovery planning. Hydrostatic primitive equations models like HYCOM and ROMS and non-hydrostatic LES models were the most commonly employed tools. Together they contributed about one third of the publications. Nevertheless, there was a great diversity of approaches employed in the 330 modeling applications and in the 74 unique models explored here.

Taken together as a suite, models developed for the study of DWH form a continuum of processes that can be linked end-to-end conceptually and often numerically. At one end, weather and ocean forecasting models are process-based and use basic physical principles like Newton's laws. They have relatively little need for empirical parameterization. At the other end, socioeconomic and human health modeling is often based on empiricism. Biological models occupy the middle ground in more than one sense. They play an important role in synthesis modeling because the interests of human beings are often affected through impacts on the health of marine populations.

Although GOMRI has sunsetted operations, what will remain are the new tools and a cadre of modeling expertise that remains relevant to addressing new environmental challenges. Spills of National Significance such as the DWH oil spill do not occur very often and the daily responsibilities of regional scientists and managers need to focus on immediate issues. During and after an accident like this one, public efforts and energy understandably need to be directed toward health and safety, environmental clean-up, and quantifying the extent of the damage for settlement purposes. For this reason, GOMRI played an important academic role, improving our understanding of the nature and risks of oil spills, particularly deep oil spills, and the vulnerabilities of natural and human systems in the GOM. This is important information if we wish to fully consider risks in the calculation of costs and benefits of oil exploration in the GOM. We recommend that scientists and managers leverage the wealth of models and data amassed by GOMRI, NRDA and others to support holistic evaluation of the benefits and risks associated with oil exploration.

DECLARATION OF COMPETING INTEREST
The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cameron Ainsworth reports financial support was provided by Gulf of Mexico Research Initiative GOMRI.

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Table 1. Model application by subject of study.

Biology	
	Atlantis
	Carbon Silicate Nitrogen Ecosystem (COSiNE) Model
	Ecopath with Ecosim
	Groningen MAchine for Chem. Simulation (GROMACS)
	HABSIM
	Matrix models
	ZOOplankton SIMulation (ZOOSIM) model
Circulation	
	ANSYS Fluent
	Hybrid Coordinate Ocean Model (HYCOM)
	Hybrid LES-Detached Eddy simulation (DES)
	Large Eddy Simulation Wall-Adapting Local Eddy-Viscosity (LES-WALE)
	MARUN
	MIT general circulation model
	National Center for Atmospheric Research Large Eddy Simulation (NCAR-LES)
	Navy Coordinate Ocean Model (NCOM)
	Oregon State University global Ocean Tide Inverse Solution (OTIS)
	Princeton Ocean Model (POM)
	Regional Ocean Modeling System (ROMS)
	Regional Oceanic Modeling System (ROMS-AGRIF)
	Stanford unstructured-grid nonhydrostatic parallel coastal ocean model (SUNTANS)
	University of Texas Bays and Estuaries 3D (UTBEST3D)
	West Florida Shelf Finite Volume Coastal Ocean Model (FVCOM)
Coupled	
	Coupled Ocean-Atmosphere-Wave-Sediment transport (COAWST) model
	The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)
Data Assimilation	
	Navy Coupled Ocean Data Assimilation (NCODA)
	Simple Ocean Data Assimilation (SODA)
Nearfield	
	Droplet formation model, (VDROP)
	Deepblow
	Finite-difference-based Large-Eddy Simulation (Hydro3D)
	Jet-droplet formation model, (VDROP-J)
	Lagrangian buoyant jet model (JETLAG)
	Large-eddy simulation model (LES)
	OIL Model Application Package for DEEPwater release (OILMAP DEEP) particle-tracking

(ICHTHYOP)
Semi-Implicit Eulerian Lagrangian Finite Element (SELFE)
Stochastic Lagrangian Aggregate Model for Sinking Particles (SLAMS)
Unified Wave INterface Coupled Model (UWIN-CM)
Oil spill/mitigation
3-D Fates Model
ADIOS
General NOAA Operational Modeling Environment (GNOME) Hydrodynamic and Oil Spill Python (HyosPy)
Oil Spill contingency and Response Model (OSCAR)
Oil Spill Risk Analysis (OSRA) model
Response Options Calculator (ROC)
Texas A&M Oilspill Calculator (TAMOC)

Table 1. (continued)

Particle tracking/oil fate
Lagrangian Trajectory Model (TRACMASS)
BIOB/BIOMARUN
Connectivity Modeling System (CMS)
HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT)
Larval TRANSport Lagrangian model (LTRANS)
Markov Lagrangian Stochastic Model
Multidimensional positive definite advection transport algorithm (MPDTA
Oil particle aggregates model (A-DROP)
OpenOil
Spill Impact Model Application Package (SIMAP)
Subsurface Oil Simulator (SOSim)
Physical chemistry
TIP5P
Reanalysis
Climate Forecast System Reanalysis (CFSR)
Biology
North American Regional Reanalysis (NARR)
Socioeconomic
Impact Analysis for Planning (IMPLAN)
Wave/turbulence
NEK5000 solver
Simulating WAves Nearshore (SWAN) and ADvanced CIRCulation (ADCIRC)
Unified Miami Wave Model (UMWM)
WAVEWATCH III
Weather/climate
AERMOD
Community Climate System Model Version 4 (CCSM4)
Community Earth System Model (CESM)
European Center for Medium-Range Weather Forecasts (ECMWF)
HYSPLIT
LW16
Navy Global Environmental Model (NAVGEM)
Navy Operational Global Atmospheric Prediction System (NOGAPS)
OBODM
Second-order Closure Integrated Puff Model with Chemistry (SCICHEM)/Second-order Closure Integrated

Puff model (SCIPUFF)
Weather Research and Forecasting (WRF) Advanced Research WRF (ARW)

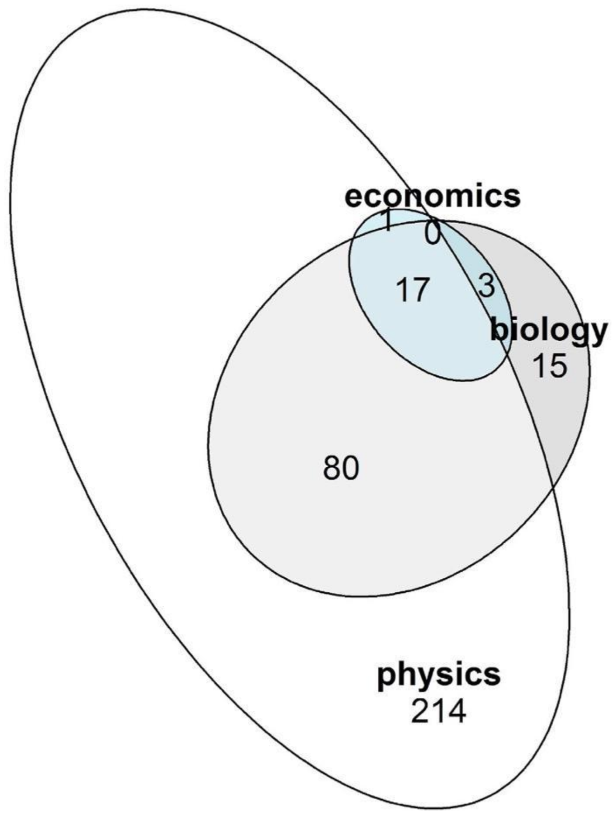

Fig. 1. Number of modeling publications and topics investigated by various GOMRI awards, NRDA and others.

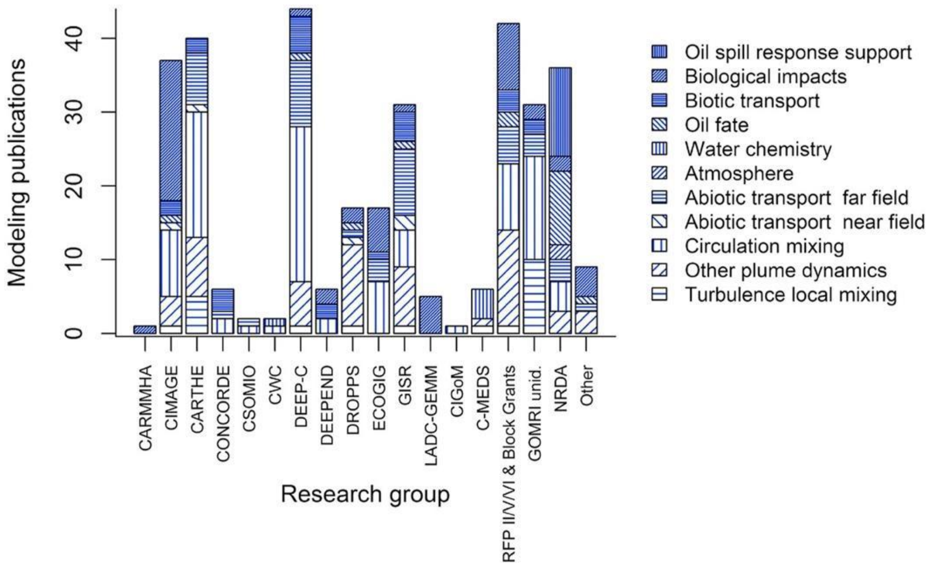

Fig. 2. DWH modeling articles and the subjects of study by consortium.

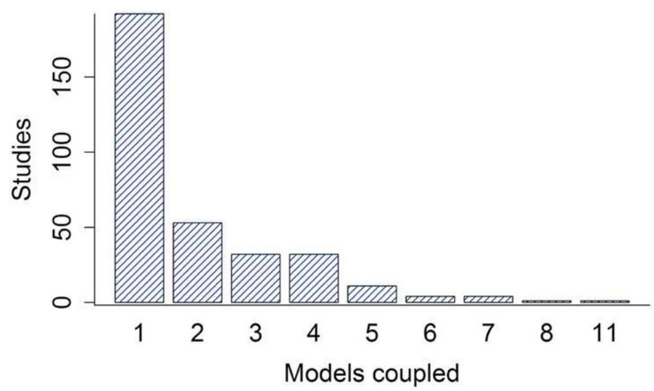

Fig. 3. Number of published models employed (coupled) per study.

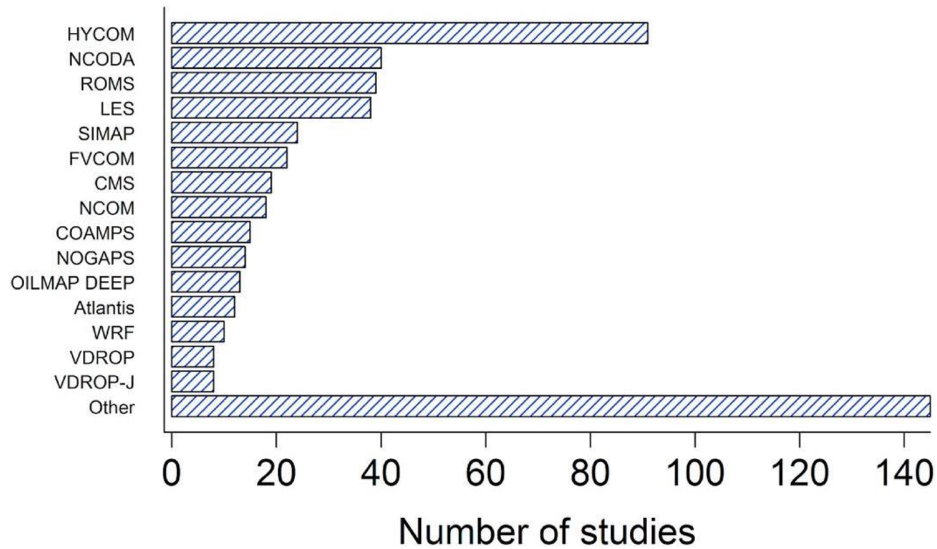

Fig. 4. Number of studies using major published modeling packages. ‘Other’ category includes 56 additional models.

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